

Using external information and GAMs to improve catch-at-age indices for North Sea plaice and sole

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External information and Generalized Additive Models (GAMs) are used to improve the indices provided by the BTS survey for the stock assessment of plaice and sole. These ancillary data consist of the following variables: Depth, Sediment grain-size, Surface temperature, Latitude, Longitude, Time of day and Day of year. Three approaches that predict the catches of four age-groups of plaice (1–4+) and sole (1–4+) were studied: (1) a “basic” GAM that incorporated the external variables; (2) A GAM where the catches of fish species other than the two target species were represented by three Principal Components (PC’s) and added to the “basic” model; (3) The predictions of the basic model were applied to a regular grid covering a slightly expanded index area.

The results are validated using two criteria: one is that of internal consistency, the other compares the estimates with the results of the stock assessments of plaice and sole without the tuning of the BTS index. Both in terms of internal consistency and correlation with the stock assessments all three methods involving GAMs performed better than the actual observed catches. The approach where the predictions of the basic model were applied to a grid performed best of all for both plaice and sole.

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Introduction

Several sources of information are used for the tuning of the stock assessment of plaice and sole: data from commercial fisheries (UK and Netherlands) as well as two research vessel surveys (e.g. Beam Trawl Survey, BTS and Sole Net Survey, SNS) (ICES, 2000). The primary objective of these surveys is to provide indices of the year-class strength of the younger age-groups (1–4+) of plaice and sole. During these surveys, catches of these two target species are recorded as are those of other fish species as well as several physical and chemical variables encountered at each site.

In a survey, the catches depend on the behaviour and distribution of the species which in turn may be determined by environmental factors such as water depth, salinity, sediment granulometric characteristics, light or food availability (Rogers, 1992; Gibson, 1994, 1997).

Generalized Additive Models (GAMs) have previously been applied to relate distributions of abundance from fish survey data to locational and environmental

covariates (Swartzman *et al.*, 1992, 1994, 1995; Augustin *et al.*, 1998; Borchers *et al.*, 1997). In the present study ancillary data are incorporated as covariates in GAMs to improve the catch-at-age indices provided by the BTS survey for the stock assessment of plaice and sole. The objectives were to (1) compare several methods that incorporate external data using GAMs and (2) determine whether this approach helps in improving the indices required for the stock assessments of plaice and sole. For this, the catches per haul of four age-groups (1–4+) of plaice and sole are predicted using GAMs and the results are evaluated using two criteria: one is that of internal consistency, the other compares the estimates with independent data (i.e. the results of the stock assessments of plaice and sole without the tuning of the BTS index).

Material and methods

The BTS survey was initiated in 1985 and is carried out in international cooperation covering both inshore and

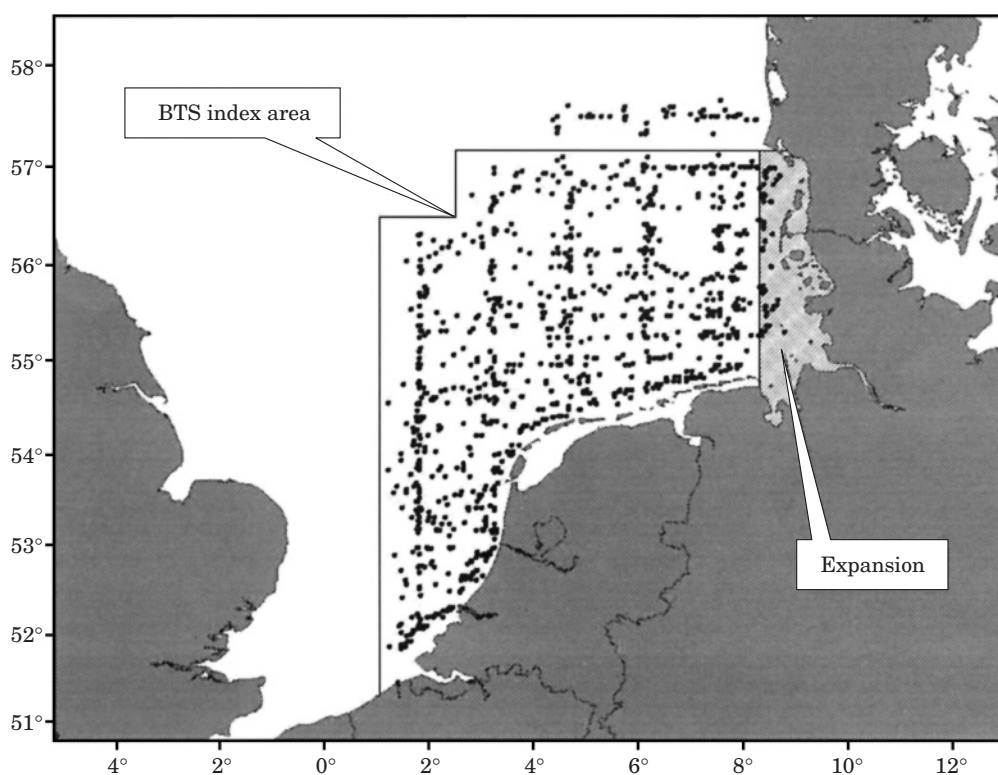


Figure 1. BTS index area and expansion covered by the grid. Positions of the hauls during the period 1985–1999 that were included in this study are indicated.

offshore areas throughout the North Sea, Channel and western waters of the UK. The survey is conducted over five weeks during August and September. The fishing gear used to collect data for the North Sea plaice and sole indices is a pair of 8 m beam trawls rigged with nets of 120 mm and 80 mm stretched mesh in the body and 40 mm stretched mesh cod-ends. A total of eight tickler chains are used, four mounted between the shoes and four from the groundrope. The survey was designed to take between one and three hauls per ICES rectangle depending on the rectangle. The stations are allocated over the fishable area of the rectangle on a “pseudo-random” basis to ensure that there is a reasonable spread within each rectangle. No attempt is made to return to the same tow positions each year. Towing speed is 4 knots for a tow duration of 30 min and fishing occurs during daylight only. From the start of BTS in 1985 until present the same research vessel (RV “Isis”) was used. At each station all fish species are measured and recorded together with physical/chemical variables such as surface and bottom temperature, depth and position in latitude and longitude. For the present study 1155 hauls within and just outside the expanded “Index area” were used (Figure 1).

To model the catches of plaice and sole in the BTS, Generalized Additive Models (GAMs) were applied. GAMs are an extension of Generalized Linear Models (GLMs) because they allow nonparametric functions to estimate the relationship between the response and the predictors (Hastie and Tibshirani, 1990). The nonparametric functions are estimated from the data using smoothing operations. Several error distributions of the data can be modelled such as a binomial, normal/gaussian or poisson. Because of the skewed distribution of the catches per haul and high proportion of 0 catches of most species-at-age it was necessary to use a two-stage GAM: first the probability that species-at-age was present (P_p) was modelled using a binomial distribution, then the log-transformed positive catches ($\log C$) were predicted using a gaussian model.

$$P_p \text{ or } \log C = \text{Year} + \text{Depth} + \text{Time} + \text{Day} + \text{Grain-size} + \text{Latitude} + \text{Longitude} + \text{Period} * \text{Depth} + \text{Period} * \text{Grain-size} + \text{Period} * \text{Latitude} + \text{Period} * \text{Longitude} + \text{Latitude} * \text{Longitude} + \text{Surface Temperature} * \text{Depth}$$

Year was added as a factor for the effect of the difference between years. More gradual change in modelling the

Table 1. Significance of variables in basic GAM model of species-at-age.

Variable	Plaice				Sole			
	1	2	3	4+	1	2	3	4+
Binomial								
Depth	0.02	0.18	0.14	0.66	0.13	0.00	0.02	0.39
Time of day	0.44	0.35	0.05	0.16	0.46	0.10	0.52	0.11
Latitude	0.01	0.35	0.01	0.00	0.00	0.00	0.00	0.00
Longitude	0.02	0.57	0.06	0.00	0.14	0.10	0.00	0.00
Day of year	0.01	0.09	0.00	0.00	0.00	0.62	0.05	0.28
Median grain-size	0.69	0.00	0.00	0.12	0.40	0.00	0.07	0.25
Latitude*Longitude	0.41	0.57	0.73	0.54	0.41	0.60	0.23	0.16
Depth*Temperature	0.08	0.04	0.00	0.25	0.04	0.01	0.07	0.03
Gaussian								
Depth	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.03
Time of day	0.18	0.01	0.12	0.02	0.02	0.01	0.00	0.00
Latitude	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Longitude	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.07
Day of year	0.02	0.39	0.31	0.02	0.11	0.11	0.27	0.01
Median grain-size	0.04	0.00	0.00	0.20	0.02	0.08	0.12	0.01
Latitude*Longitude	0.02	0.00	0.01	0.09	0.26	0.05	0.02	0.19
Depth*Temperature	0.00	0.00	0.30	0.29	0.03	0.00	0.15	0.15

Bold values are significant at $p \leq 0.05$.

fishes distribution over time was incorporated by distinguishing three five-year periods (i.e. 1985–1989, 1990–1994 and 1995–1999) using a factor *Period*. The relationship of the catch with the external factors was modelled using a cubic smoothing spline. In order to acquire relatively smooth and interpretable relationships with all external factors except for the geographical position the degrees of freedom were restricted to 3 (grain-size, time of day and day of year) or 5 (depth). This two-stage GAM was used for each species-at-age.

In order to correspond to the arithmetic mean of the untransformed data the predicted catch (C_e) was calculated as follows:

$$C_e = P_p * \exp(\log C) * \exp(0.5 \sigma^2)$$

where σ is the square root of the deviance divided by the degrees of freedom.

Three different approaches were studied using the basic two-stage GAM. (1) The first approach used only the basic two-stage GAM. (2) In addition to the basic GAM the catches of fish species other than the two target species, represented by three Principal Components (PCs), were used as linear explanatory variables in both the binomial and gaussian part of the model. For the Principal Component Analysis (PCA) all fish species other than the two target species were selected that over the entire sampling period contributed more than 0.1% to the total catch in numbers. (3) In contrast to the first two approaches where the predictions were applied to the sampled positions only, the third approach applied

the predictions to a regular grid (raster 2' longitude \times 4' latitude) of 1482 gridpoints covering an index area expanded to the east up to the coastline (Figure 1). At each gridpoint the following data were available: geographical position in latitude and longitude, depth and mean sediment grain-size. The time of day was arbitrarily set at 12 noon, the day of year was set at the 1st September and surface temperature was set equal to the mean surface temperature of that year.

Depth data for positions other than the BTS stations were based on Kriging of the depth data in the ICES hydrographic database. Median grain-size was based on data from the 1986 Benthos survey (Craeymeersch *et al.*, 1997) complemented with data from the Danish Institute for Fisheries Research in Hirtshals irregularly placed in the central North Sea. The target variable, called "median-phi" was derived from the median diameter of grains in the sediment by a logarithmic transformation [$\phi = -\log_2(\text{diameter})$]. Median-phi values range from 0–4 defining four classes: coarse sand (0–1), medium sand (1–2), fine sand (2–3) and very fine sand (3–4).

Abundance indices per year for both the observed catches and the output of the first two approaches (basic GAM and basic GAM+PCs) were calculated according to BTS protocol: mean abundance per species-at-age was first calculated per ICES rectangle after which the arithmetic mean per year was determined over all ICES rectangles inside the BTS index area. For the GAM method with a grid the arithmetic mean over all gridpoints was calculated. The GAMs were applied using the Splus 2000 software package.

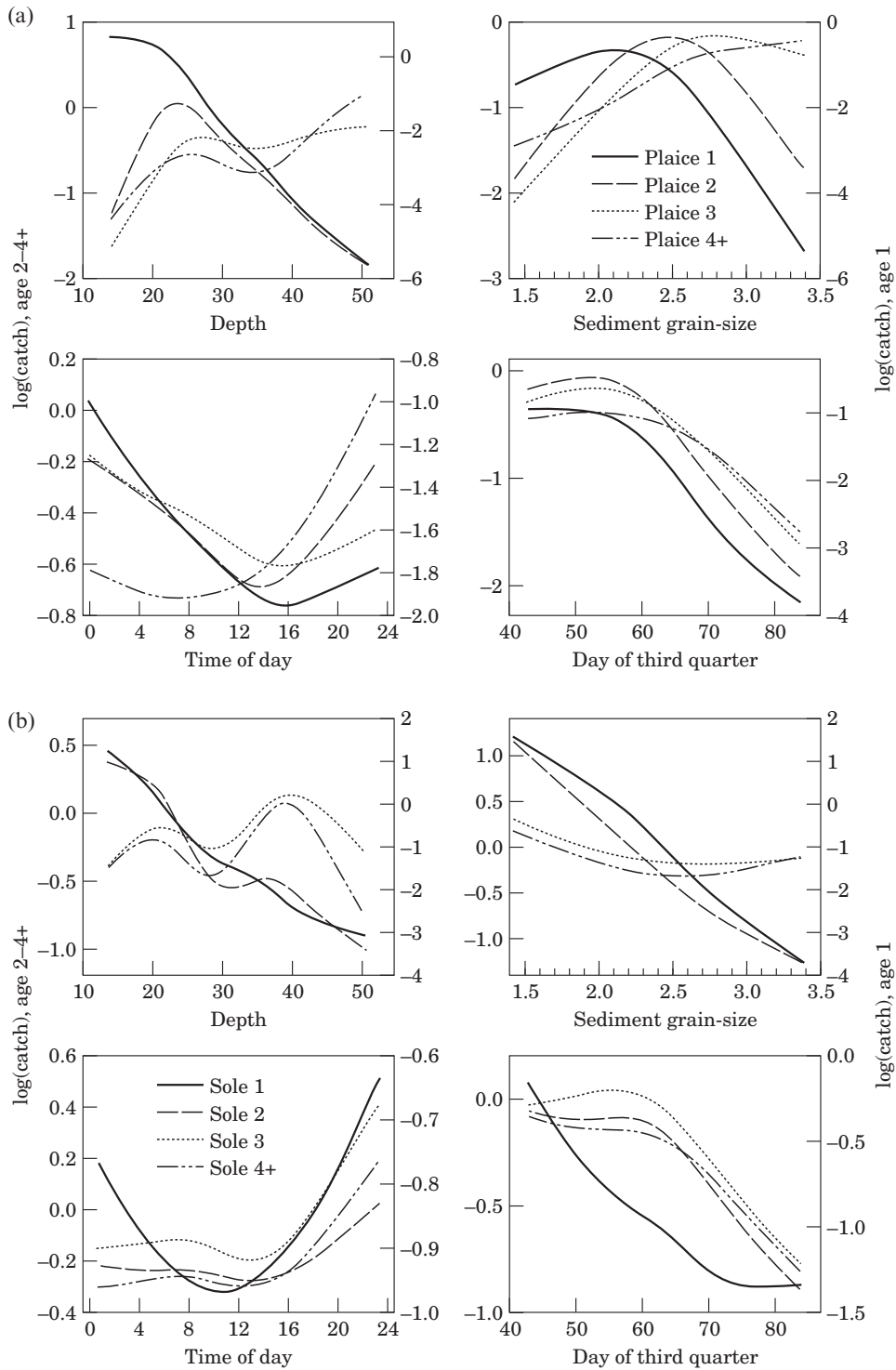


Figure 2. Relationships determined with cubic smoothing splines of catches-at-age of plaice (a) and sole (b) with four covariates used in the GAM models.

Table 2. Principal component loadings per species and explained variance per principal component. Indicated is also the contribution of each species (%) to the total catch in numbers.

Species	%N	PC 1	PC 2	PC 3
<i>Buglossidium luteum</i>	5.7	0.17	-0.03	0.10
<i>Echiichthys vipera</i>	2.3	0.10	-0.34	-0.01
<i>Callionymidae</i>	5.7	0.10	0.27	0.13
<i>Gobiidae</i>	2.4	0.00	-0.10	0.08
<i>Gadus morhua</i>	0.2	-0.01	0.14	0.22
<i>Agonus cataphractus</i>	2.6	0.08	-0.15	0.04
<i>Hippoglossoides platessoides</i>	0.2	-0.16	0.03	-0.27
<i>Limanda limanda</i>	68.3	0.14	0.49	-0.10
<i>Microstomus kitt</i>	0.2	0.06	0.15	0.11
<i>Merlangius merlangus</i>	4.5	-0.11	-0.03	0.38
<i>Myoxocephalus scorpius</i>	0.2	0.17	0.10	-0.36
<i>Platichthys flesus</i>	0.2	0.21	-0.39	-0.08
<i>Rhinonemus cimbrius</i>	0.2	-0.03	-0.07	0.42
<i>Arnoglossus laterna</i>	3.6	-0.04	-0.10	-0.01
<i>Scophthalmus maximus</i>	0.1	0.21	0.19	0.21
<i>Trigla lucerna</i>	0.3	0.23	0.27	0.20
<i>Trisopterus luscus</i>	0.9	0.07	-0.04	0.35
<i>Trisopterus minutus</i>	0.1	-0.02	0.00	0.06
<i>Eutrigla gurnardus</i>	2.0	-0.24	0.23	0.02
Explained variance (%)		38.3	24.3	16.5

For comparison of the trajectories of the abundance indices of each species-at-age the observed and predicted abundances were normalized by subtracting the mean and dividing this by the standard deviation for that trajectory.

Two methods were used to validate the (observed and predicted) time series: (1) first an internal validation was used based on the assumption that the decrease in cohort strength from age A to age A+1, age A+1 to age A+2, etc. is consistent over time. Therefore the mean catch per year of species-at-age A in year Y was correlated using linear regression with species-at-age A+1 in year Y+1, species-at-age A+2 in year Y+2 and species-at-age A+3 in year Y+3, (2) the mean catch of species-at-age A in year Y was correlated using linear regression with the calculated stock abundance in numbers as derived from the assessments using Extended Survivors Analysis (XSA, Darby and Flatman, 1994; Shepherd, 1999) excluding the BTS index. This correlation was done for the period (1985–1995) during which the assessment is likely to have converged.

Results

The basic two-stage GAM model used to predict the catches of the species-at-age was based on six variables: depth, time of day, latitude, longitude, day of year, median grain-size and surface temperature. All these variables were included for each stage and species-at-age but only some showed a statistically significant contribution (Table 1). The relationships between the positive catches and the external factors as established using

cubic smoothing splines differ markedly between the species-at-age (Figure 2). The abundance of the younger age-groups of plaice and sole decreases with increasing depth which does not apply to the older age-groups. These younger age-groups of plaice and sole in turn differ in their preference of sediment type: sole appears to prefer “medium sand” (phi 1–2) whereas plaice prefers “fine sand” (phi 2–3). Both avoid “very fine sand” (phi 3–4). Catch numbers of most species-at-age are higher in the early morning and at night. Catch numbers decrease as sampling takes place later in the third quarter.

For the second approach in which catches of fish species other than the two target species were added to the model, Principal Component Analysis on 19 species revealed three PCs that explained nearly 80% of the variance in this assemblage (Table 2).

Yearly estimates of the catches based on the observed catches and the three different GAM methods are shown for each of the species-at-age (Figure 3). Although minor differences are observed between the trajectories the overall pattern appears robust. The species-at-age with the largest differences between the trajectories is age 1 Plaice. This age-group shows three strong years e.g. 1986, 1988 and 1997. The abundance index of 1986 is higher according to the observed catches and the GAM method applied to a grid than when based on the basic GAM method with or without PCs. The opposite was observed for the 1997 abundance index. The 1988 abundance index is high in all trajectories. Only the observed catches of age 1 Plaice show a relatively high abundance index in 1992. The main difference between the

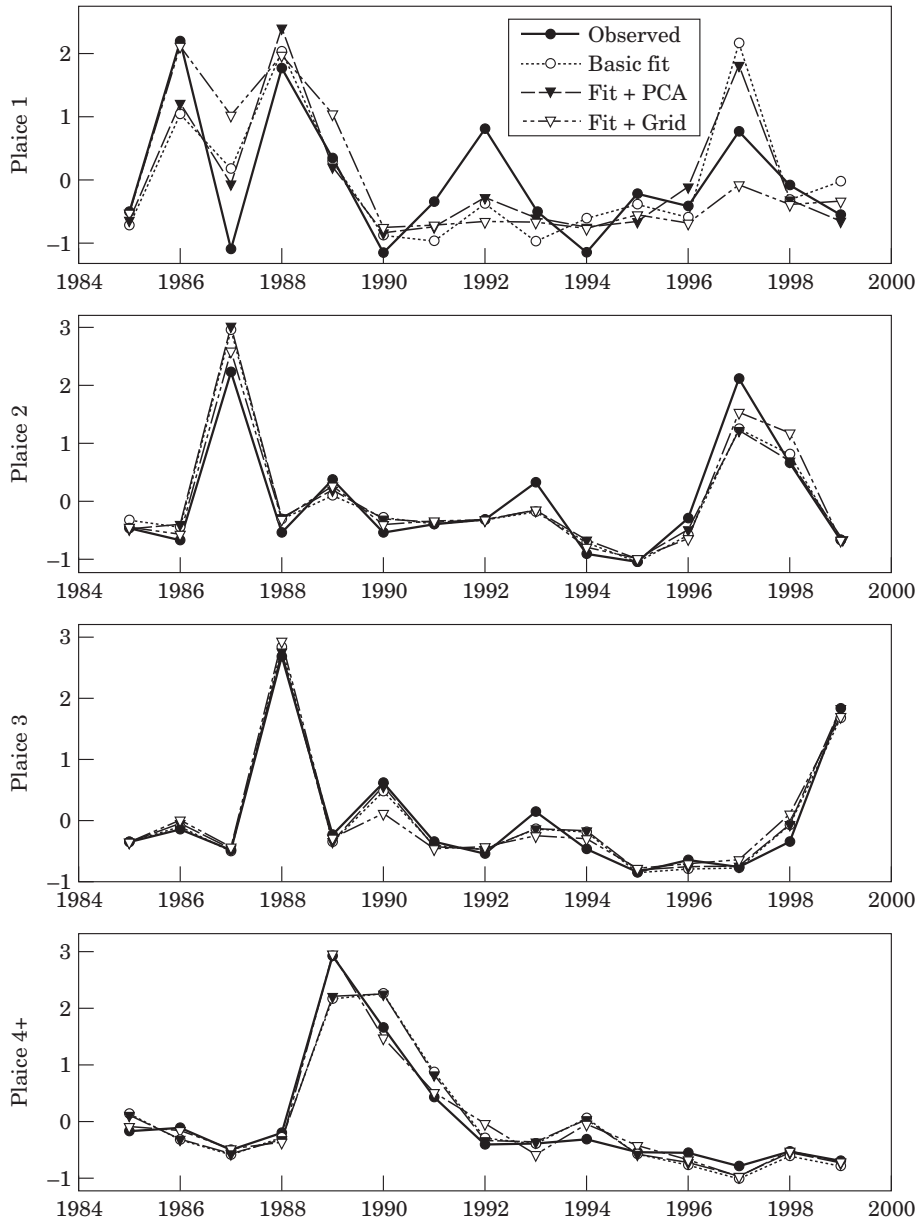


Figure 3. (a).

trajectories of age 2 Plaice lies in the contrast between the observed catches and the fitted catches. In 1987 and 1998 the observed catches give a lower abundance index whereas in 1993 and 1987 the resulting abundance index is higher. For Sole the main differences between trajectories were observed for ages 1 and 4+. For age 1 Sole mainly the trajectories based on the observed catches and/or that based on the model applied to a grid deviated. For age 4+ it was only the trajectory based on the observed catches.

For validation two approaches were used: internal consistency and correlation with the stock assessment output. In terms of overall (all species-at-age) internal consistency all GAM methods perform better than the observed catches and the model applied to a grid performs best of all (mean $R^2=0.52$) (Table 3).

Correlation with the stock assessments without BTS shows a pattern similar to that based on internal consistency: all GAM methods perform better at providing abundance indices in agreement with the assessments

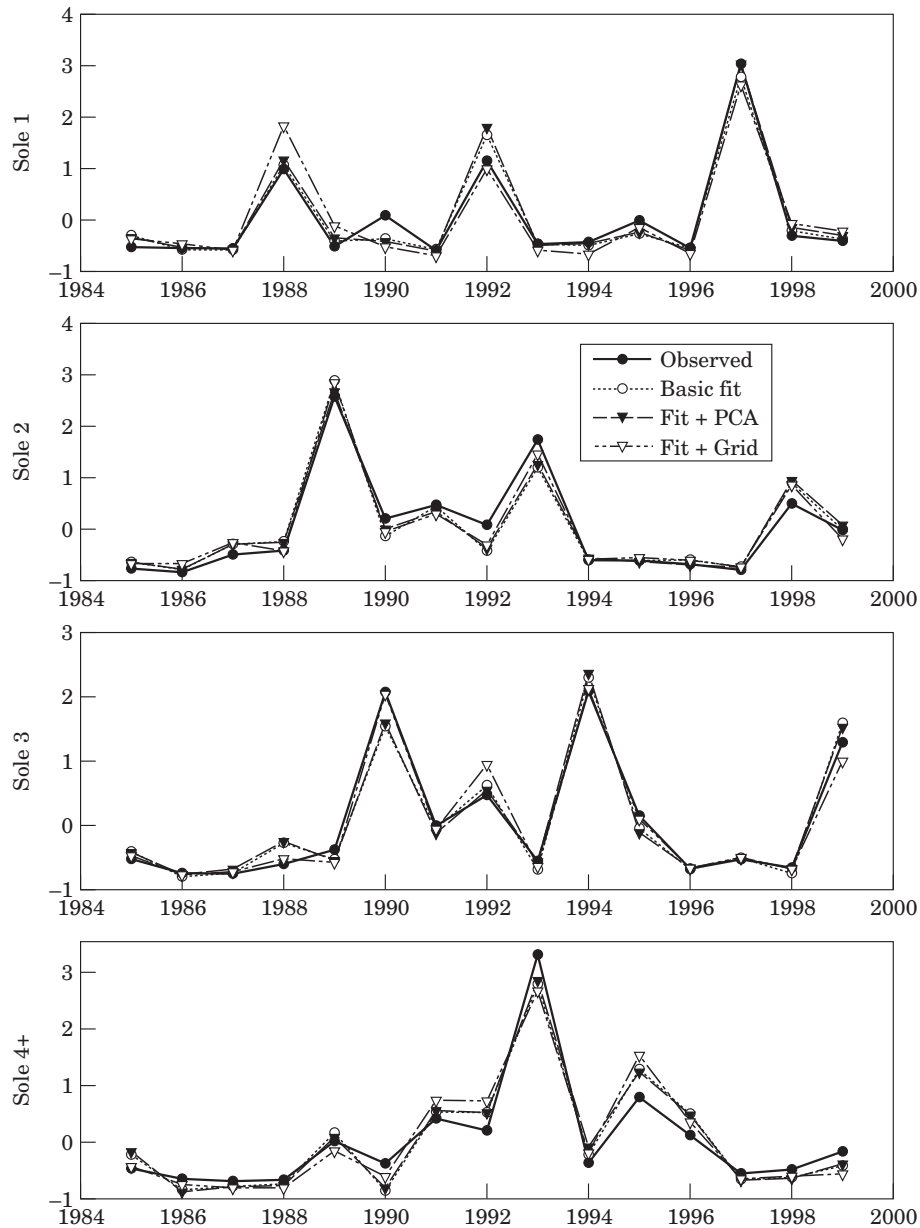


Figure 3. (b).

Figure 3. Trajectories of yearly catch-at-age BTS indices of plaice (a) and sole (b) predicted according to four different methods: Observed catches, Basic GAM method, Basic GAM method+three PCs and basic GAM method applied to a grid.

than do the observed catches (Table 4). The model applied to a grid performs best overall (mean $R^2=0.81$), as well as for plaice (mean $R^2=0.78$) and sole (mean $R^2=0.84$) separately. There are, however, differences in model performance between the various species-at-age (Table 4). Compared to the observed catches only age 1 plaice and sole show a significant (F-test, $p<0.01$) improvement using the model applied to a grid.

Discussion

The aim of this study was not only to describe the spatial distribution of the fish but to try to provide improved abundance indices using the GAMs. Two methods of validation were used to assess the accuracy of the abundance indices. The fact that both methods of validation display similar results strengthens the conclusions based on the validation.

Table 3. Validation through internal consistency of the different methods.

	1	2	3	4+	Plaice
OBS					
1		0.37	0.57	0.27	0.40
2	0.34		0.44	0.22	0.35
3	0.59	0.85		0.70	0.57
4+	0.16	0.20	0.25		0.40
Sole	0.36	0.46	0.56	0.20	0.41
BAS					
1		0.24	0.50	0.41	0.39
2	0.47		0.80	0.31	0.45
3	0.74	0.73		0.45	0.58
4+	0.12	0.25	0.47		0.39
Sole	0.45	0.48	0.65	0.28	0.46
PCA					
1		0.31	0.56	0.32	0.40
2	0.53		0.76	0.33	0.46
3	0.79	0.76		0.47	0.60
4+	0.12	0.24	0.42		0.37
Sole	0.48	0.51	0.65	0.26	0.47
GRID					
1		0.24	0.31	0.68	0.41
2	0.63		0.81	0.45	0.50
3	0.56	0.84		0.69	0.60
4+	0.14	0.32	0.61		0.61
Sole	0.44	0.60	0.67	0.36	0.52

Method indicated upper left: OBS=observed catches, BAS=basic method, PCA=basic method+PCs, GRID=basic method applied to a raster grid). Matrix shows R² between the age-group combinations. Upper right shows R² for plaice, lower left for sole. Mean per age group are in the right column (plaice) and the bottom row (sole). The overall mean R² of each method is shown in the lower right corner.

Table 4. Results (R²) of linear regression between stock assessment output and GAM methods (for abbreviations see Table 3) per species-at-age.

Method	Plaice					Sole					Overall mean
	1	2	3	4+	Mean	1	2	3	4+	Mean	
OBS	0.48	0.79	0.85	0.81	0.73	0.87	0.90	0.85	0.37	0.75	0.74
BAS	0.34	0.91	0.88	0.80	0.73	0.81	0.93	0.82	0.53	0.77	0.75
PCA	0.34	0.89	0.87	0.80	0.73	0.81	0.93	0.83	0.53	0.78	0.75
GRID	0.53	0.88	0.91	0.80	0.78	0.89	0.95	0.85	0.65	0.84	0.81

The above results show that GAMs can be useful to describe the spatial distributions of fish using smooth functions of several covariates. Provided that the main covariates (depth, latitude and longitude) are included, the addition of more covariates or change of the degree of smoothing does not appear to affect the abundance indices substantially in spite of the fact that they often do change the predicted catch per haul per year significantly. Therefore in the GAM model only those covariates were incorporated (often with a restriction on the degrees of freedom) for which interpretable and plausible relationships could be expected (see Rogers, 1992; Gibson, 1994, 1997).

Incorporating the interaction between the 5-year periods and the main external factors that determined the distribution of the species-at-age (depth, latitude and longitude) was necessary to describe a gradual shift in distribution further offshore observed for mainly the younger plaice and sole. The relevance of these periods might be based on two factors: (1) the introduction of the “plaice box” a closed area in the south-eastern North Sea and (2) a marked increase in water temperature in the (expanded) index area during the last decade.

To reduce the discarding of plaice in the nursery grounds along the continental coast of the North Sea, an area between 53°N and 57°N was closed to fishing for

trawlers with engine power of more than 300 hp in the second and third quarter since 1989, and for the whole year since 1995. These measures resulted in a marked shift of fishing effort to offshore areas that has possibly affected the distribution of the fish. During the BTS survey the mean surface temperature increased from 16.5°C in the first 5-year period to 17.0°C in the second to 18.3°C in the final 5-year period. The increased water temperature has the strongest impact on demersal species such as plaice and sole in shallow areas where the bottom temperature resembles surface temperature (Piet *et al.*, 1998). The increasing temperatures in the past decade possibly caused fish to avoid the shallow areas with highest bottom temperatures.

For plaice and sole it was decided to apply the GAM to the whole dataset with a factor added for a year-effect instead of to each year separately. The advantage of this was that this allowed establishing one interpretable relationship between catch-at-age and a particular external variable for the whole dataset. Applying GAM to separate years not only resulted in different relationships per year but often these relationships were difficult to interpret biologically.

The fact that the application of the GAM to a regular grid covering an expanded index area rendered the best results suggests (1) that the difference between years in the external variables and notably the positions sampled may be a source of bias and (2) that the incorporation of the expansion of the index area into the sampling program and calculation of the indices may result in improved indices of North Sea plaice and sole.

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